Array based analysis of the induced seismicity in Helsinki, southern Finland

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The st1 Deep Heat geothermal stimulation experiment in Espoo, Finland

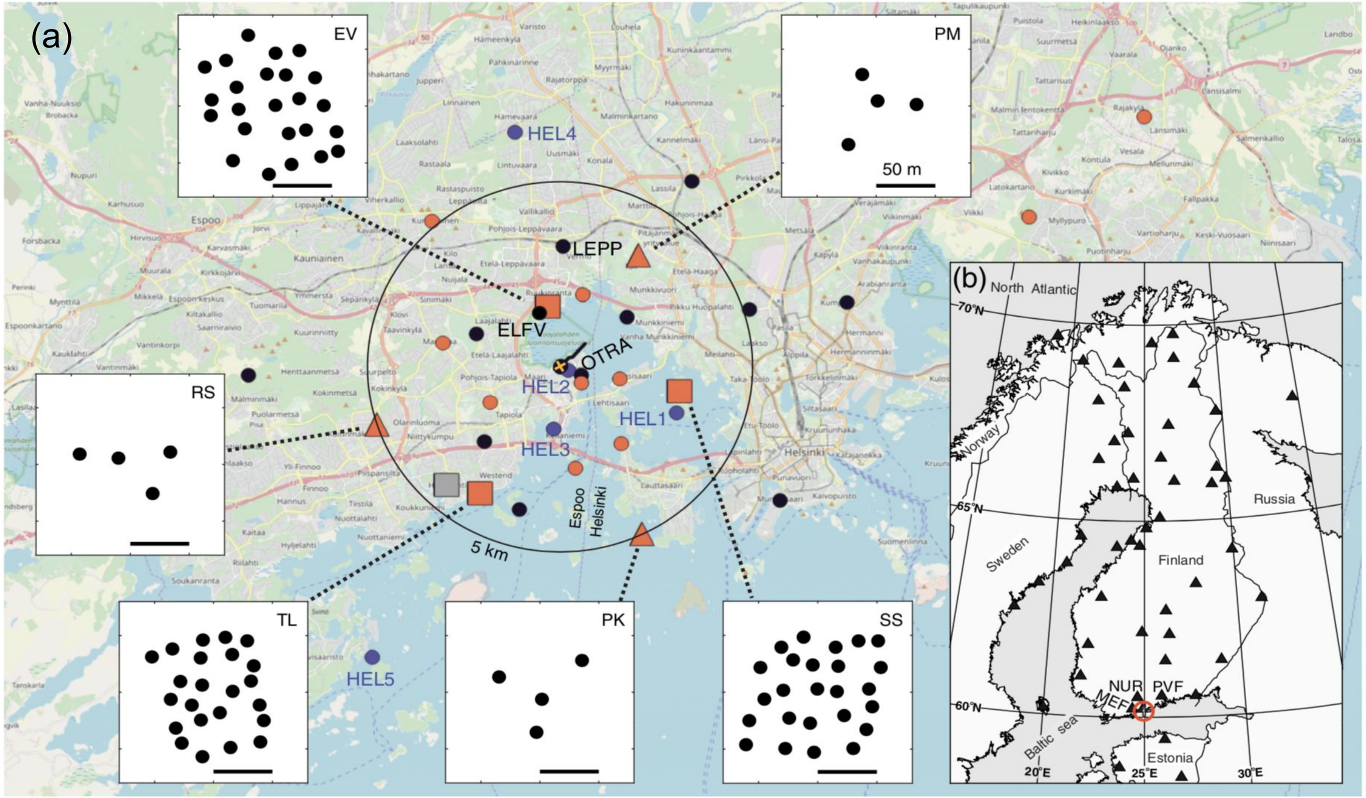
~6.1 km deep OTN-3 geothermal stimulation experiment from 4 June to 22 July 2018

Seismic network:

12 borehole stations (black circles)

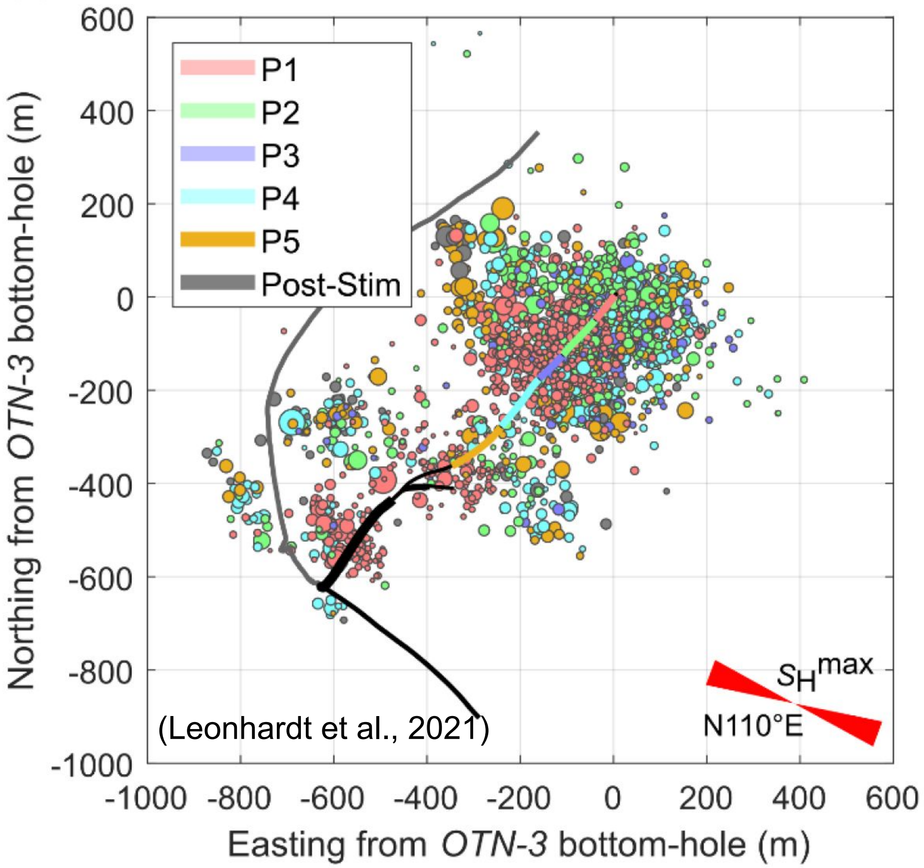
5 broadband HEL stations (blue circles)

100 geophones (red symbols)



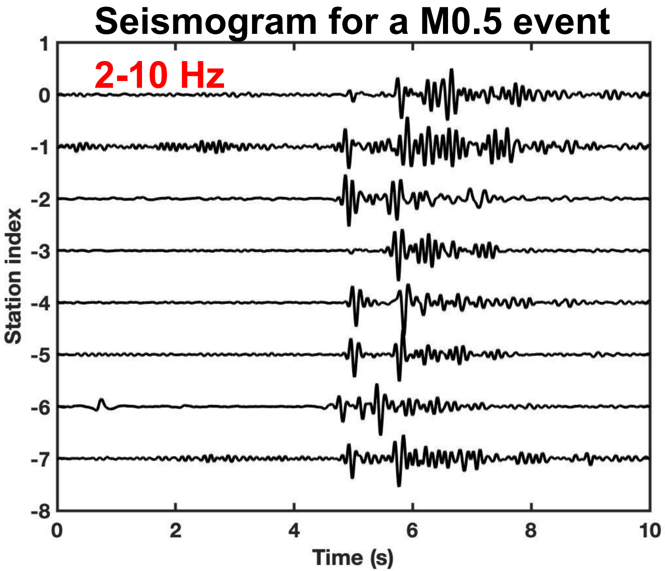
(Hillers et al., 2020)

Induced seismicity



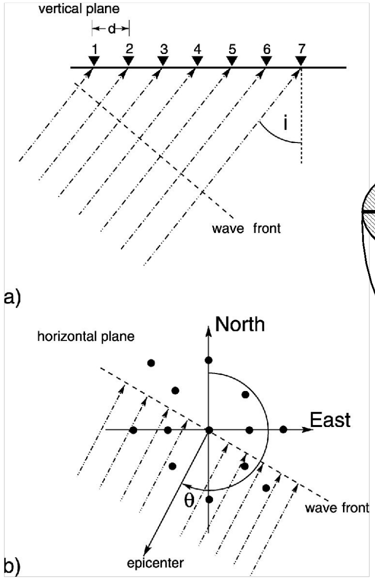
Thousands of induced seismicity with magnitude ⩽ M_L1.8

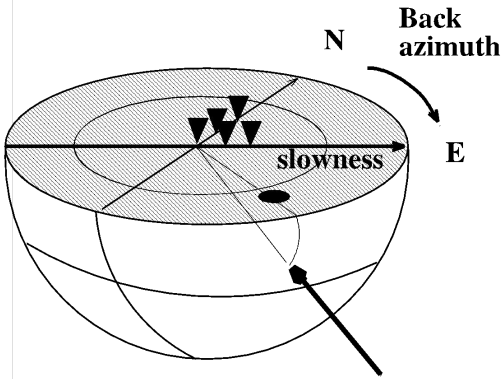
The absence of a dissipating sedimentary layer results in high signal-to-noise ratio (SNR) seismograms



Array Methods

Beamforming

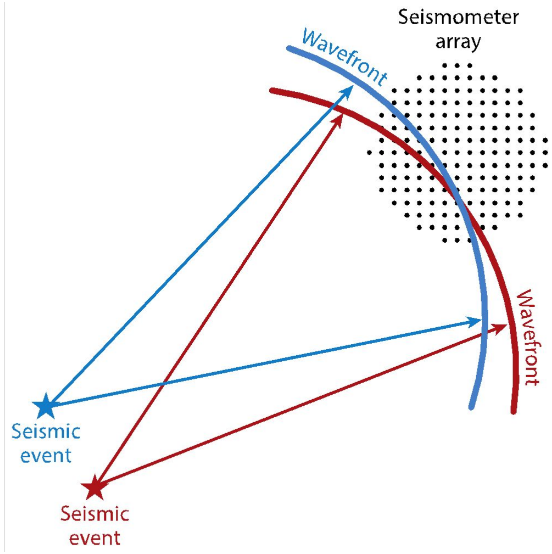




(Rost & Thomas, 2002)

Use the differential travel times of the plane wavefront in a small array due to specific slowness and back azimuth to individual array stations to determine source directions (Rost & Thomas, 2002).

Back-projection



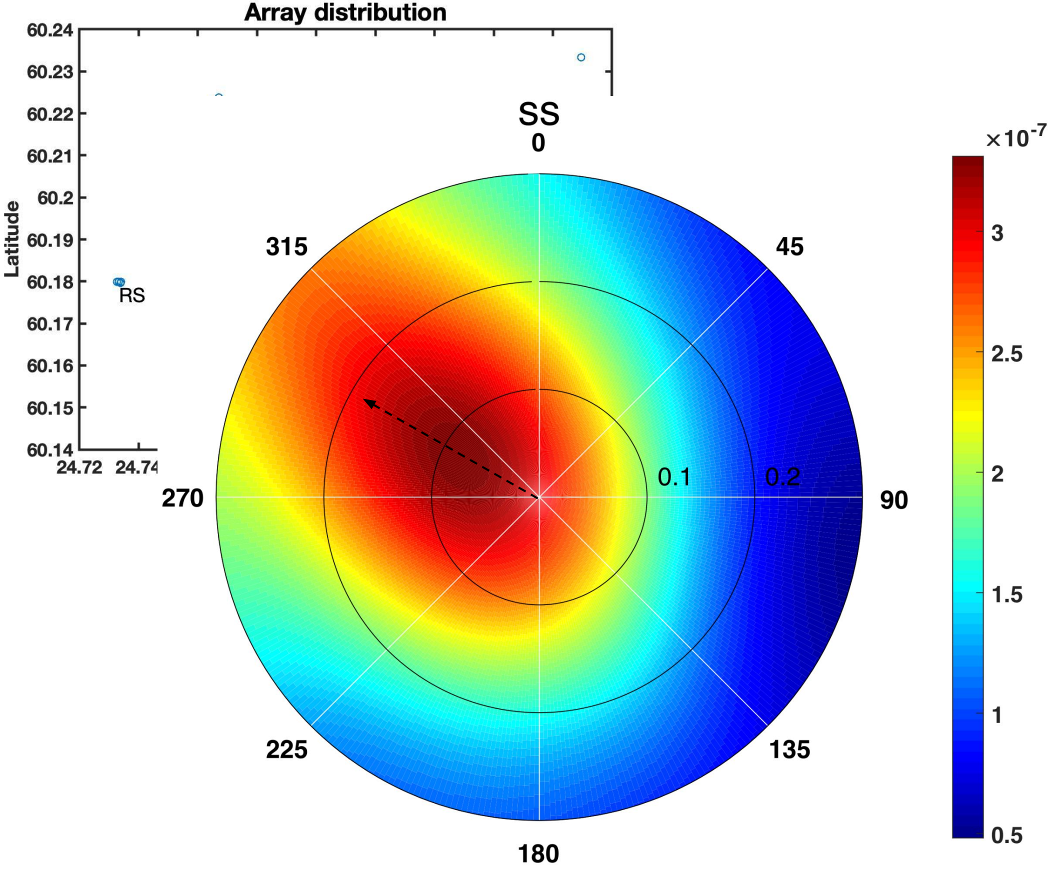
http://www.seismology.harvard.edu/research/backproj.html

Use the curvature of the wavefront recorded at large aperture, dense seismic arrays and the time reversal property of these coherent waves to determine the time and location of their sources (Ishii et al., 2005).

It has been widely used to image the rupture process of many large and moderate earthquake, with teleseismic arrays.

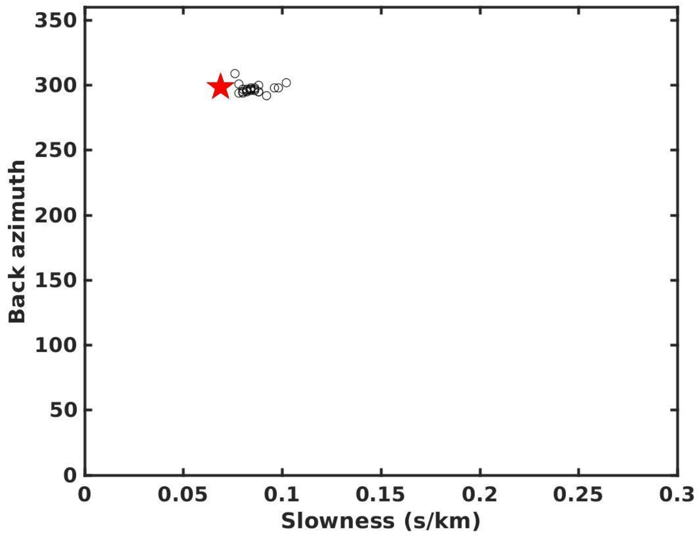
We extend its application to the study of induced seismicity at local scales.

Beamforming



Bootstrapping

Each time we select (n-1) stations out of n stations in the mini array

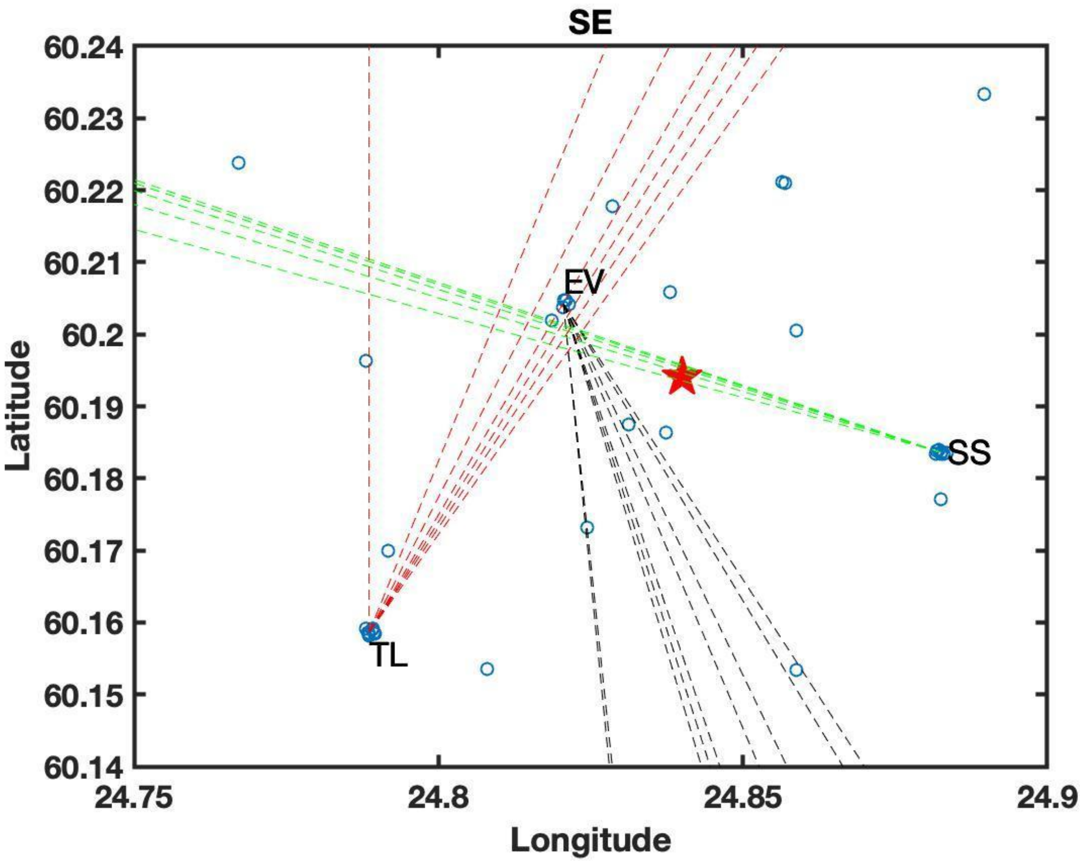


Beamforming

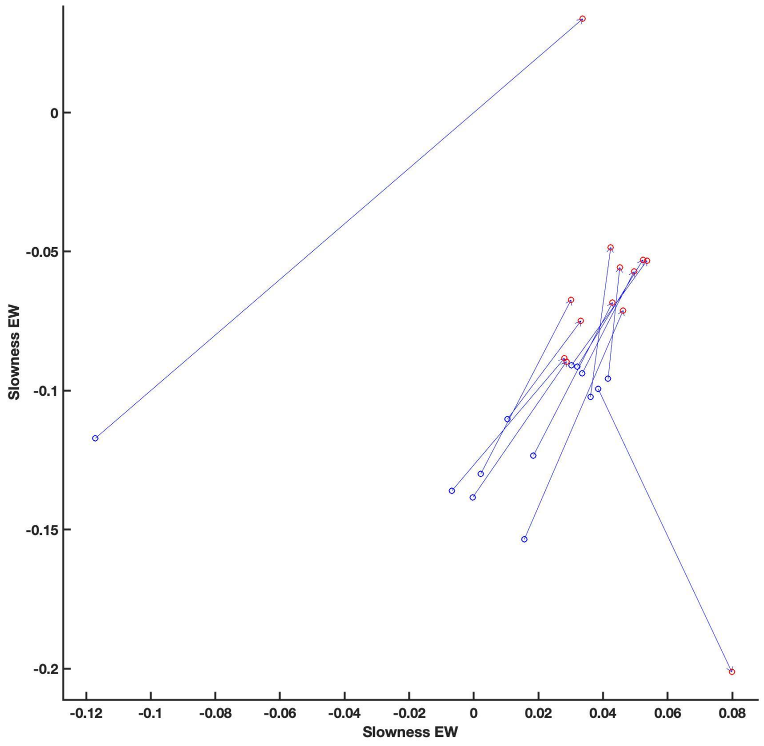
The back azimuth of the slowness doesn’t point to the event location?

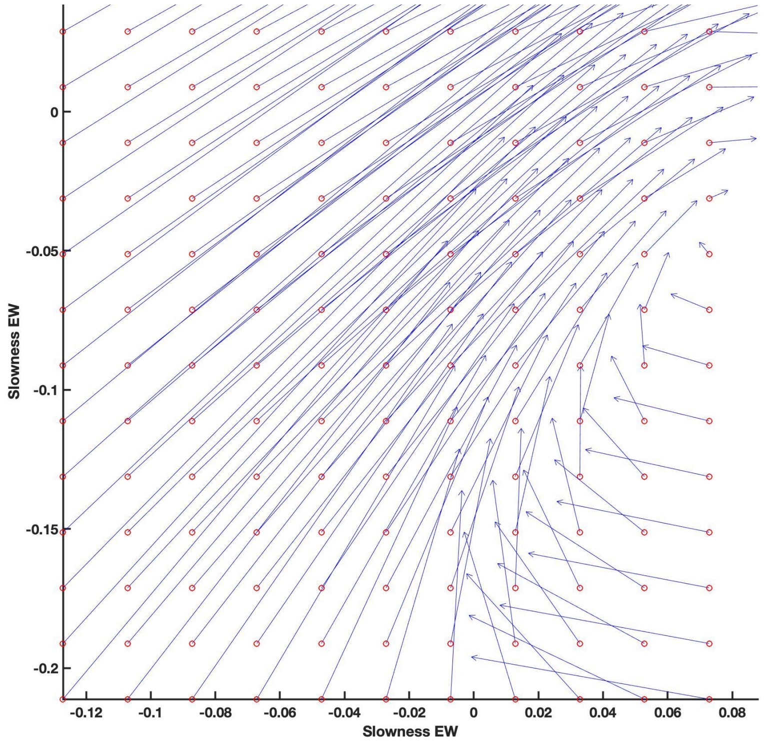
Heterogeneity under the array and travel path relative to source.

The systematic bias can be reduced through calibration with the events, which locations are well constrained

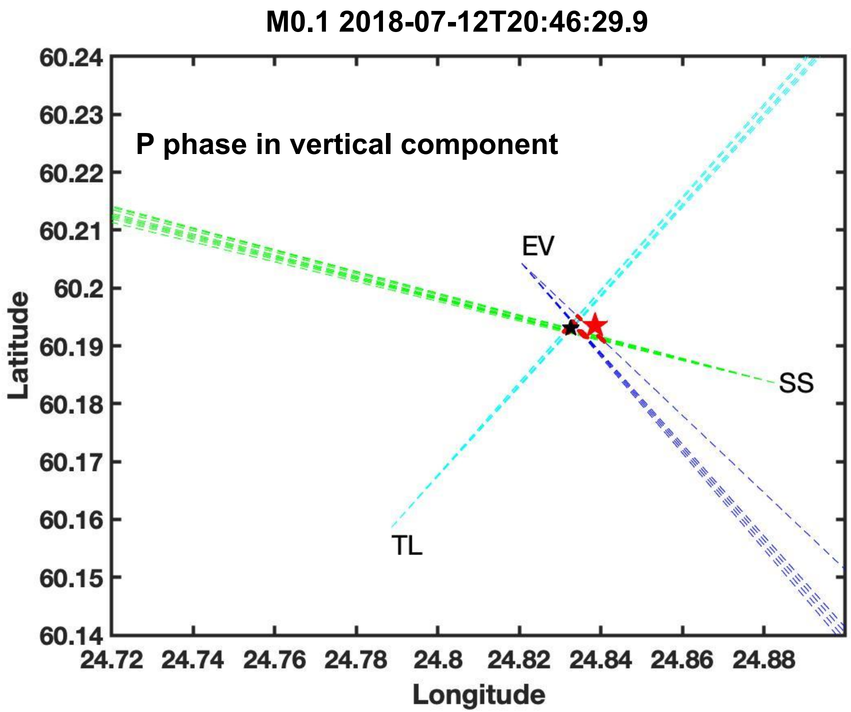


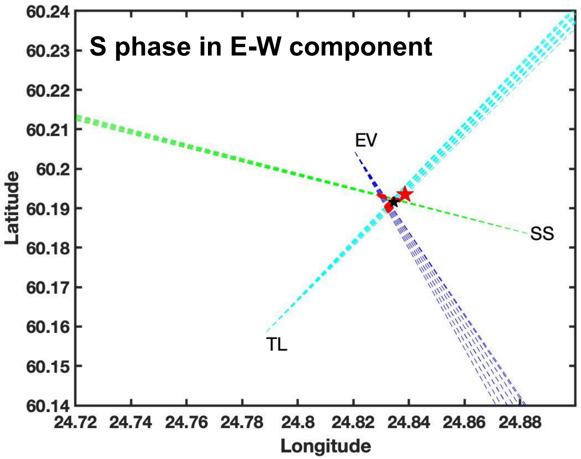
Beamforming-calibration

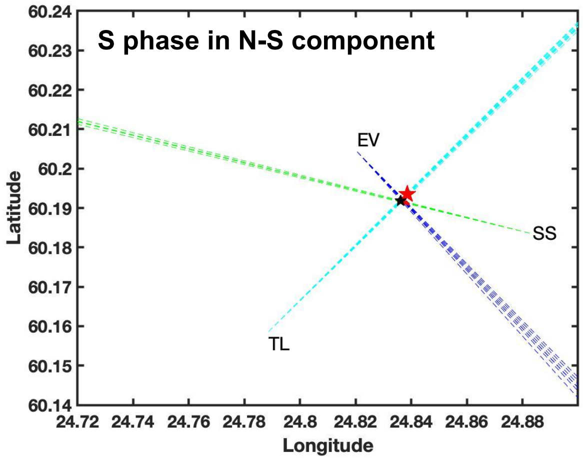




Beamforming



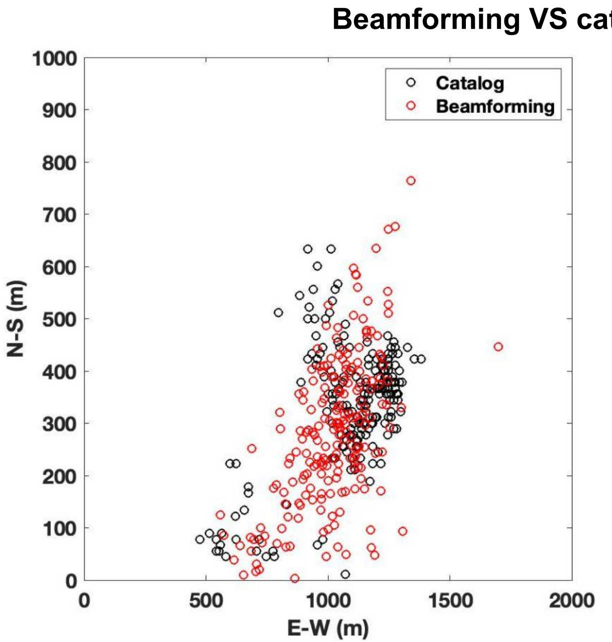


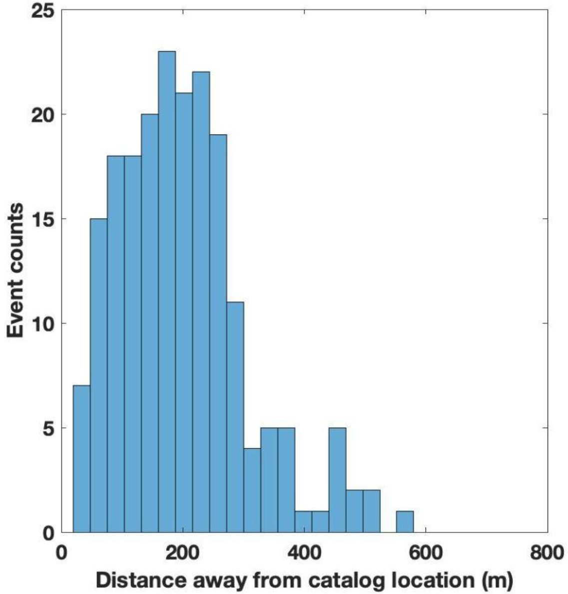


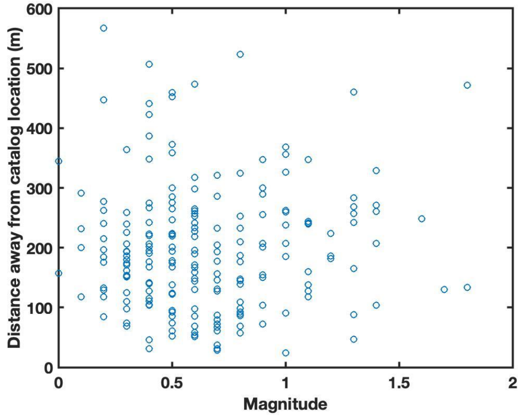
After calibration, the back-azimuth ray tracing can intersect and points to the source direction

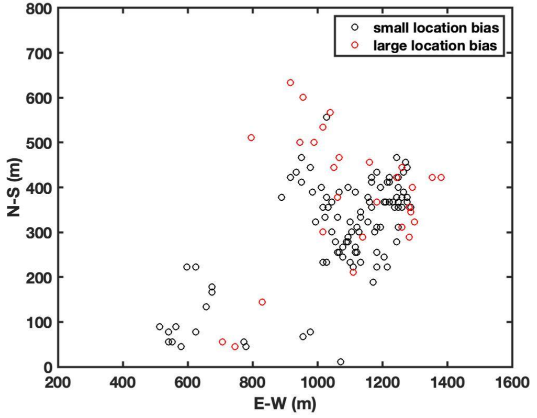
Both P and S phases work with beamforming, even for small magnitude events

Beamforming









The beamforming show similar distribution as the catalog events along the injecting trace

Beamforming location bias relative to the catalog:

1) There is no particular relation to the magnitude
2) Large location bias more distributed at the deep boundary of the seismicity patch

Beamforming

With a velocity model, it's able to do 3D back-slowness ray tracing to constrain the depth.

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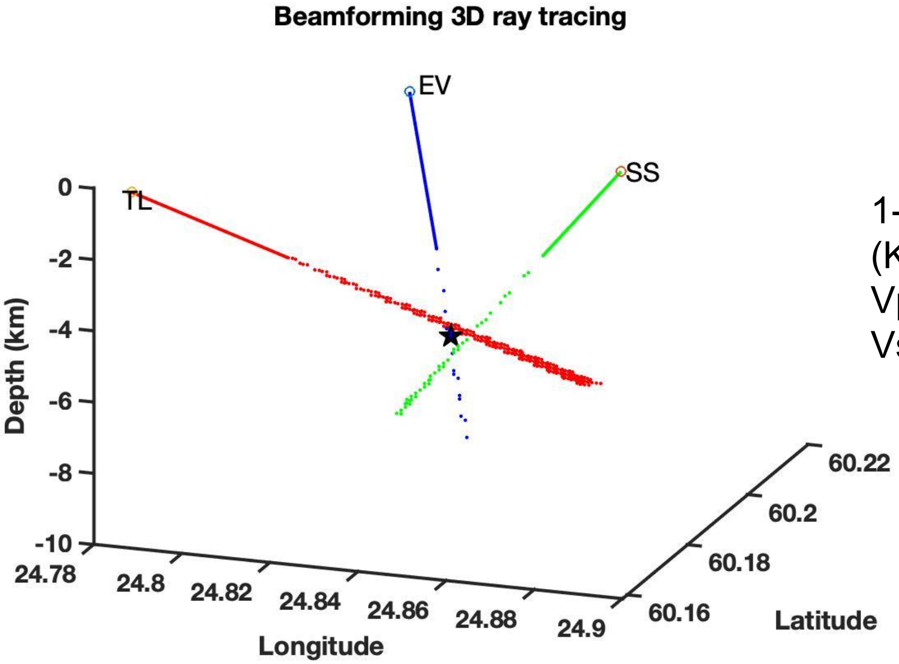
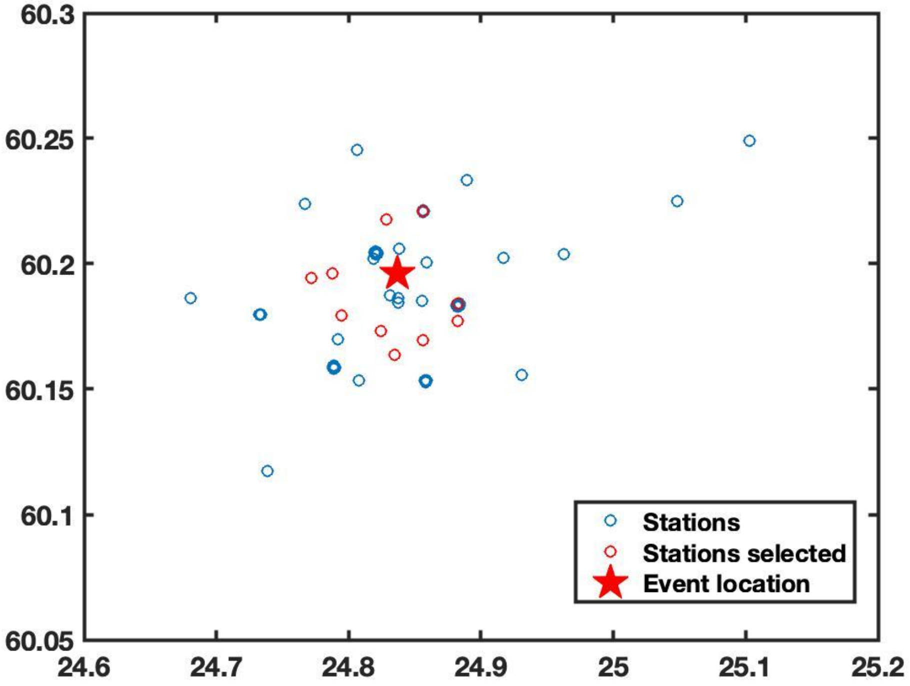


1-D homogeneous velocity model (Kortstrom et al., 2018):
Vp: 6.2 km/s
Vs: 3.62 km/s

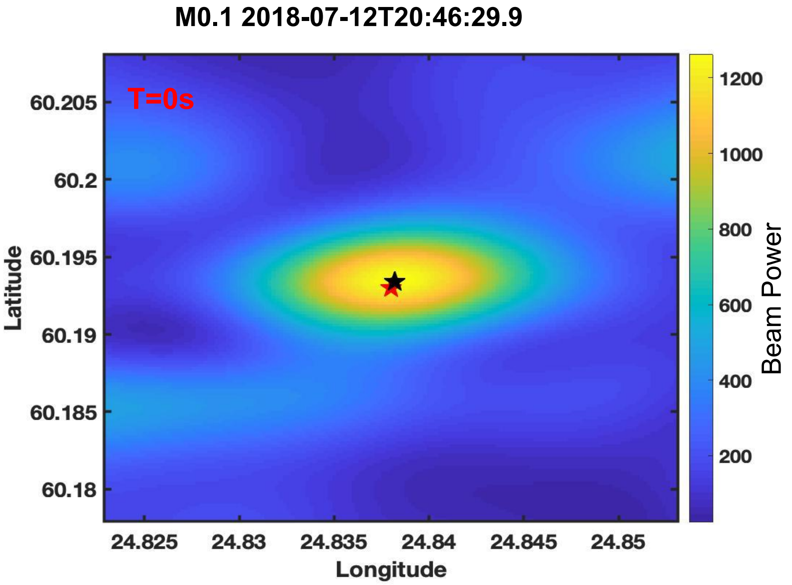
Back-projection (BP)



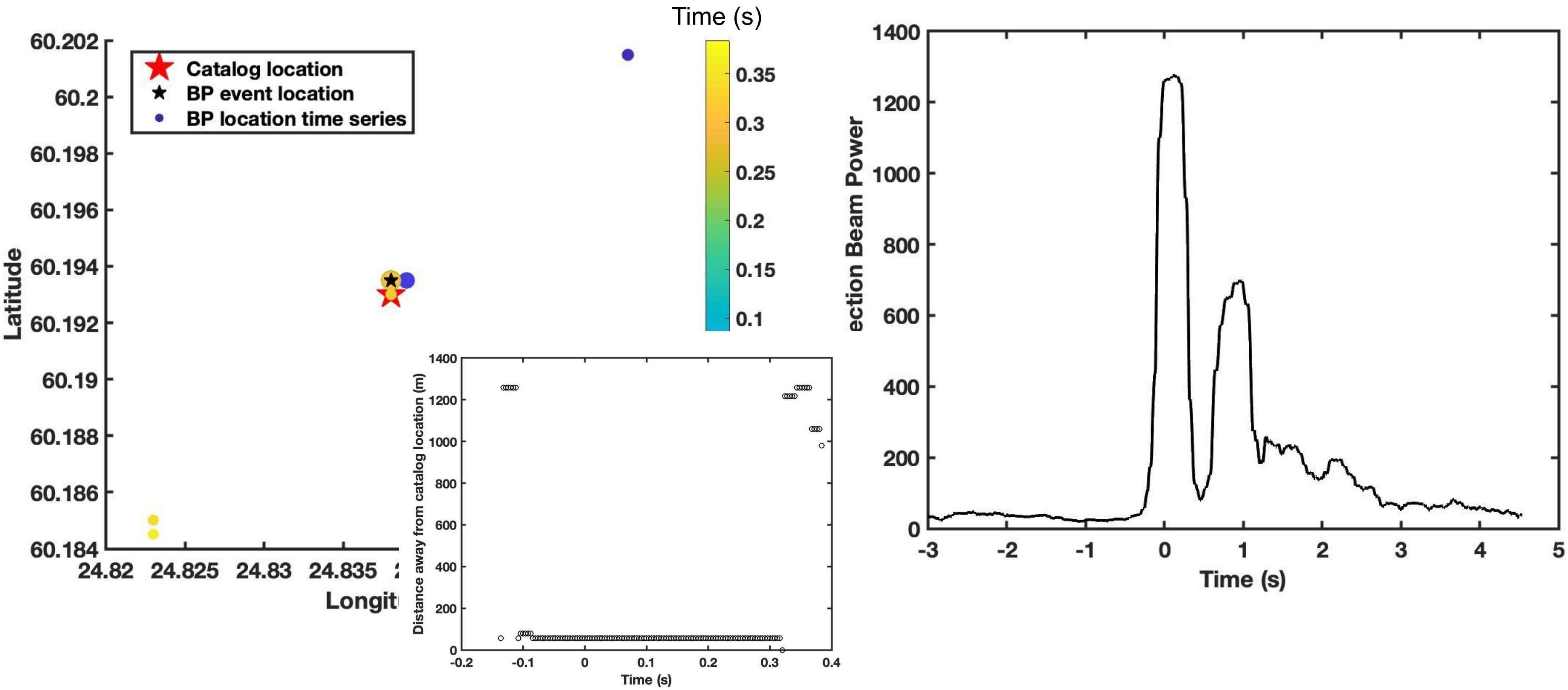
Stations in a narrow distance range: 2-4 km epicentral distance

High coherence signal stations

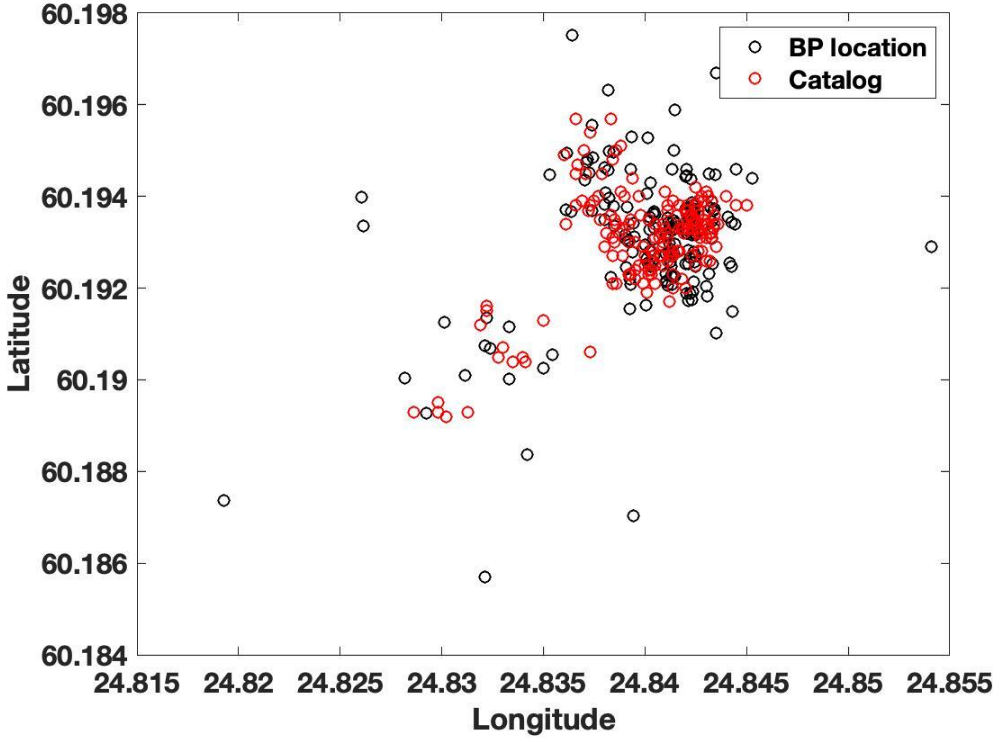
Only one station in each clustered mini array

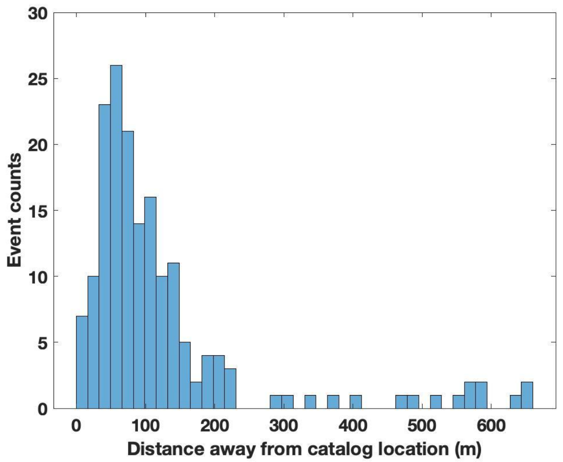


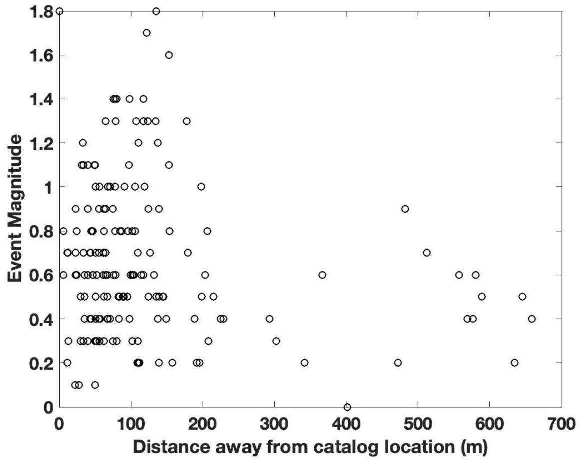
Back-projection (BP)



Back-projection

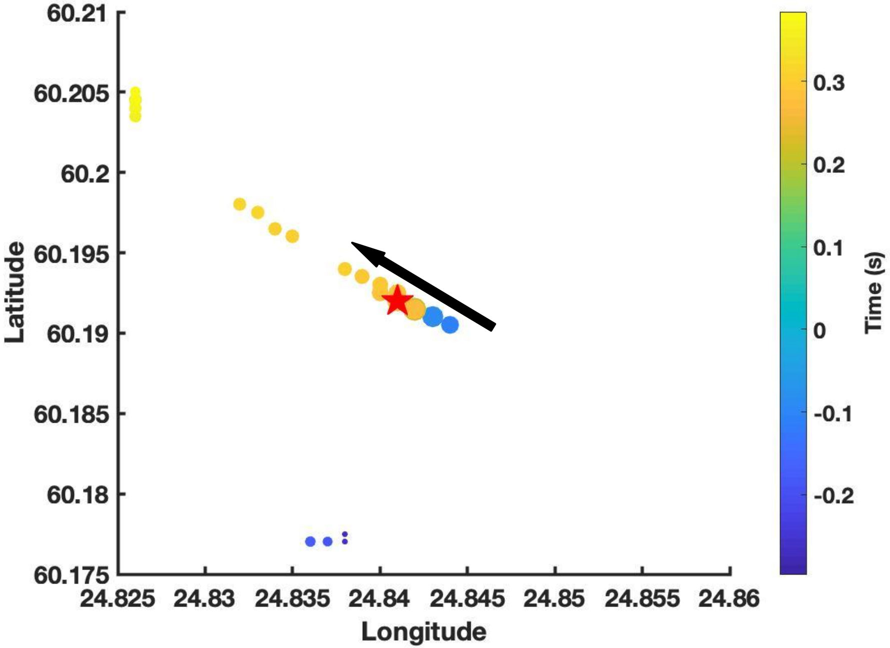


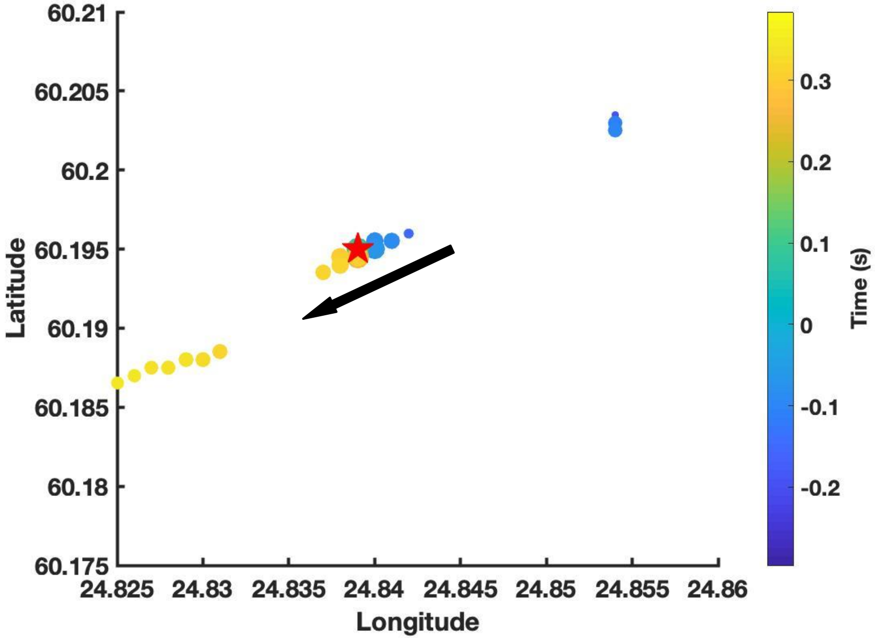




BP is able to locate the small induced events using local stations
BP locations show similar distribution pattern as the catalog
Generally large location bias only for smaller magnitude events

Back-projection:“swimming” pattern

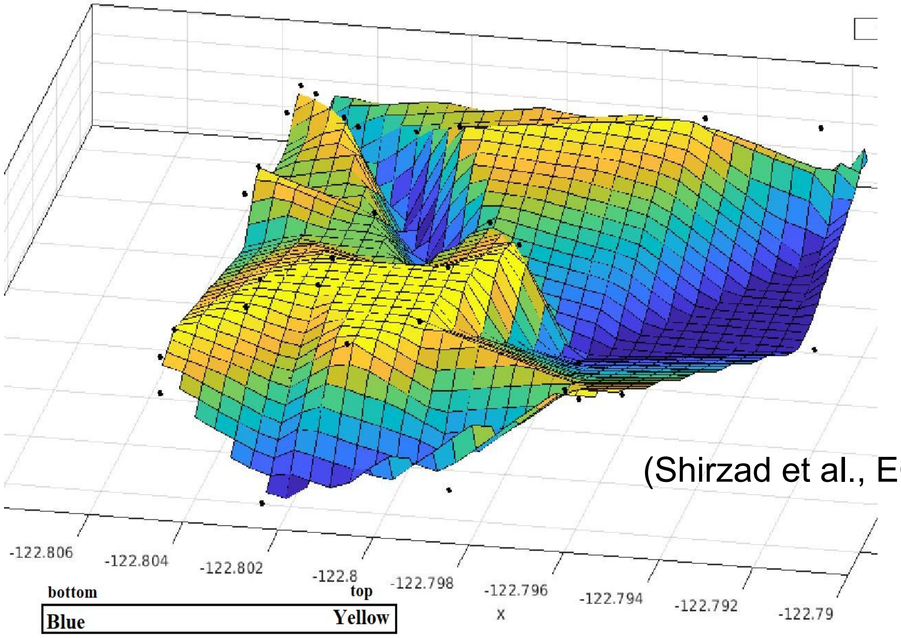




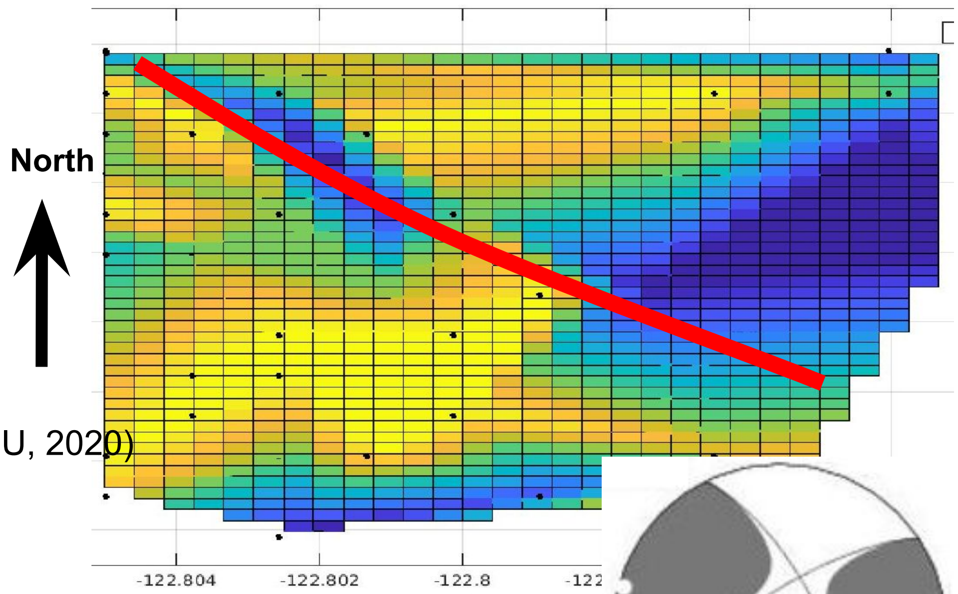
Swimming pattern: focal mechanism?

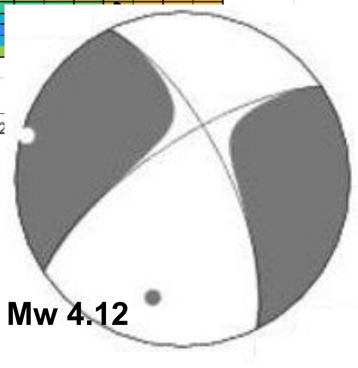
Back-projection: Focal Mechanism

Rupturing result: 3D-view



Rupturing result: 2D-view (horizontal slice)





(Shirzad et al., EGU, 2020)

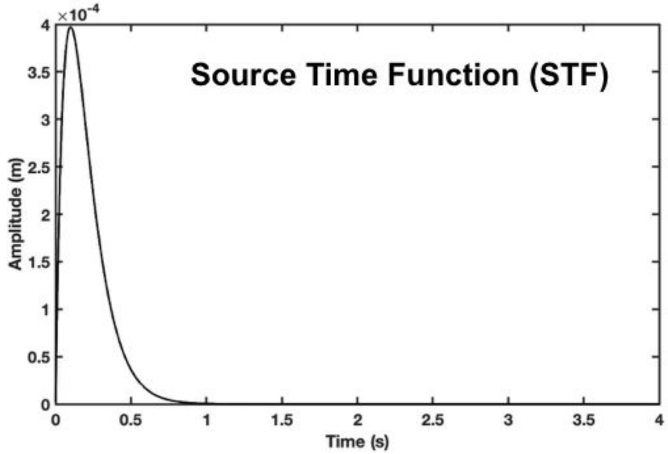
3D back-projection results can provide source mechanism estimates (Shirzad et al., EGU, 2020)

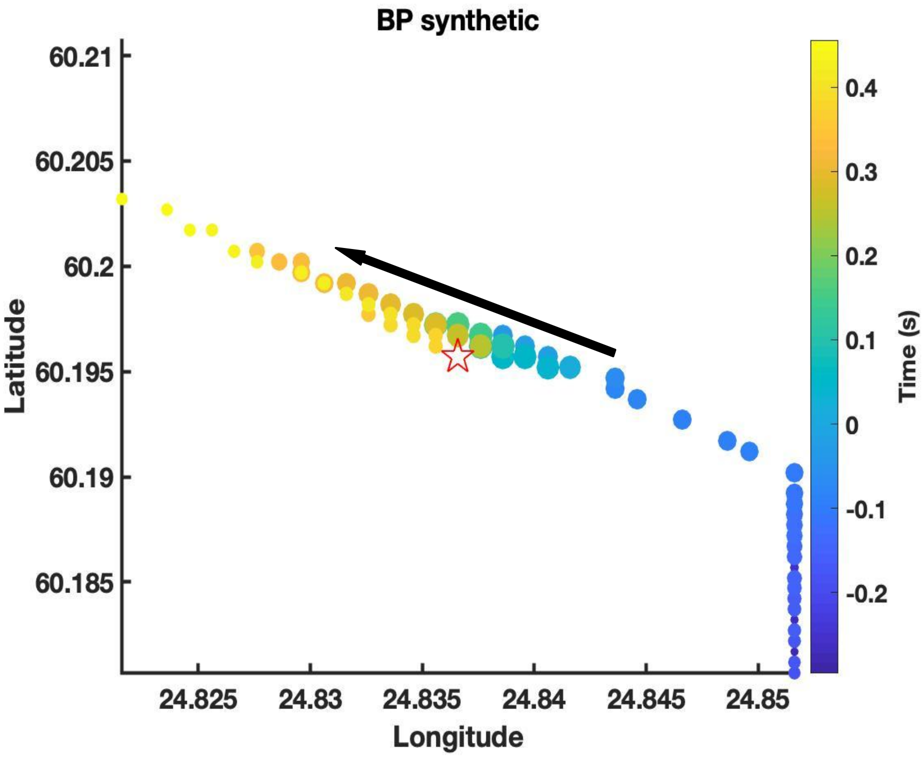
Back-projection: point source simulation

Moment Tensor [Nm]: Mnn = -0.837 Mee = -7.511, Mdd = 8.348,
Mne = -3.017, Mnd = -1.434, Med = 5.243   [x 1e+16]
Fault plane 1 [deg]: strike = 328, dip = 31, slip-rake =   71
Fault plane 2 [deg]: strike = 171, dip = 61, slip-rake = 102

Source depth: 6.09 km
Homogeneous velocity model (Vp=6.2 km/s; Vs=3.62 km/s)

Same array configuration as station used in BP





Summary

Beamforming and Back-projection can be applied to locate small induced seismicity, using local stations

Calibration of the systematic slowness uncertainty significantly improve the beamforming locations

We observe various “swimming” patterns in the BP, which can be related to the source focal mechanism